Failure Analysis of Beta-C Titanium Alloy High-Pressure Vessels

G.J. Feng, J.D. Rossi, and M.T. Gerusky

An attempt has been made to apply the linear elastic fracture mechanics concept to Beta-C titanium alloy pressure vessels that exhibited brittle fractures during hydrotesting. Based on the results of stress analysis on the real structures and fracture surface examinations, a stress-intensity factor, K_{IC}, was estimated. The K_{IC} value of the material in the cracking direction was measured by a surface semi-elliptical crack method. It was found that the K_{IC} value of the material is very close to the estimated stress-intensity factor K_I during failure, which places the pressure vessels in a critical condition in that a small variation in flaw size may cause a catastrophic failure. A compromise must be made between K_{IC} and the required yield strength. In this restricted case, the yield strength of the material should be controlled in the range of 1150 to 1200 MPa to avoid brittle fracture and the possible occurrence of yield during hydrotesting. Control of microstructure and other mechanical properties is also discussed in this investigation.

Keywords

Analysis, Beta-C titanium, failure analysis, fracture mechanics, high pressure resource

1. Introduction

LINEAR elastic fracture mechanics (LFEM) analysis has been widely utilized in failure analysis to determine cracking criteria and the cause of failure. For a given crack geometry, the stress condition in the crack tip can be described by stress-intensity factor K_I. The crack propagation will take place when K_I reaches a critical value, K_{IC}, which is presumed to be a material constant and independent of crack length and sample size. However, engineering components always contain defects to some extent due to metallurgical and fabrication processes. These defects can act as cracks if the component is in a stressed condition. When the stress level is given in a system, the maximum allowed dimension of the defect in the material is defined as critical flaw size below which the K_I value will be less than the K_{IC} value and a brittle fracture will not occur.

An attempt has been made to apply this concept to high-pressure vessels that exhibited brittle fracture during hydrotesting. The vessels were made from thin-wall seamless tube of Beta-C titanium alloy with a nominal composition (wt%) 3Al, 8V, 5Cr, 4Mo, 4Zr and heat treated to a strength of 1240 MPa. It was found that one of the vessels cracked under 94% of the designed proof pressure during hydrotesting. For materials with a high tensile strength and yield strength, failure below the proof load during hydrotesting may lead to a catastrophic failure during service. The object of this investigation was to determine the cause of the failure based on the fracture mechanics point of view. The investigation consisted of stress analysis of the structure, mechanical property testing, fracture surface examination, and microstructure analysis.

G.J. Feng, J.D. Rossi, and **M.T. Gerusky**, Westmoreland Mechanical Testing & Research Inc., Youngstown, PA 15696.

2. Fracture Surface Examinations

Figure 1 is a schematic illustration of the high-pressure vessel, which is a seamless tube with welds at either end in the circumferential directions. The investigation was conducted on two identical vessels—vessel 1, which failed at 94% proof pressure, and vessel 2, which was loaded to the proof pressure without fracture then uploaded until a burst occurred. The broken vessels were reassembled to map the fracture path and determine the origin of cracking. The crack paths of the two vessels were almost identical, and it consisted of a straight fracture of 200 mm long in the middle of the tube and followed by two separate fracture paths running at 45° through the base material to the welds at either end. One hypothesis was that the fracture may have originated from the weld. The fracture path as described above (see Fig. 1) is inconsistent with this hypothesis in that it indicates that fracture began in the center of the vessel at some point along the straight fracture area. A thorough examination of the fracture surface confirmed this fact. At the weld locations, the crack passed through the weld but never followed the fusion line or the heat-affected zone. No evidence of weld/parent metal separation was observed. Most importantly, a small semi-elliptical surface crack was found on the outer diameter of pressure vessel 1 (failed hydrotesting) in the straight fracture region. The crack measured 6.1 mm in length and had a maximum depth of 0.76 mm. Fracture surface examination using scanning electron microscopy (SEM) revealed that the fracture mode throughout the entire region defined by the semi-elliptical boundary was dominated by intergranular

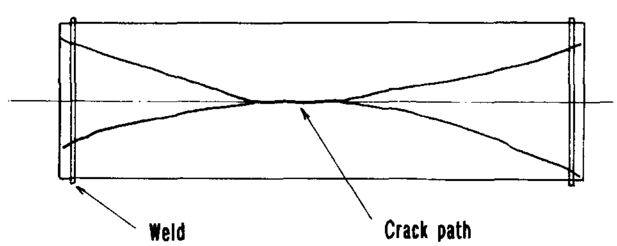

Fig. 1 Schematic of the pressure vessel and its fracture paths.

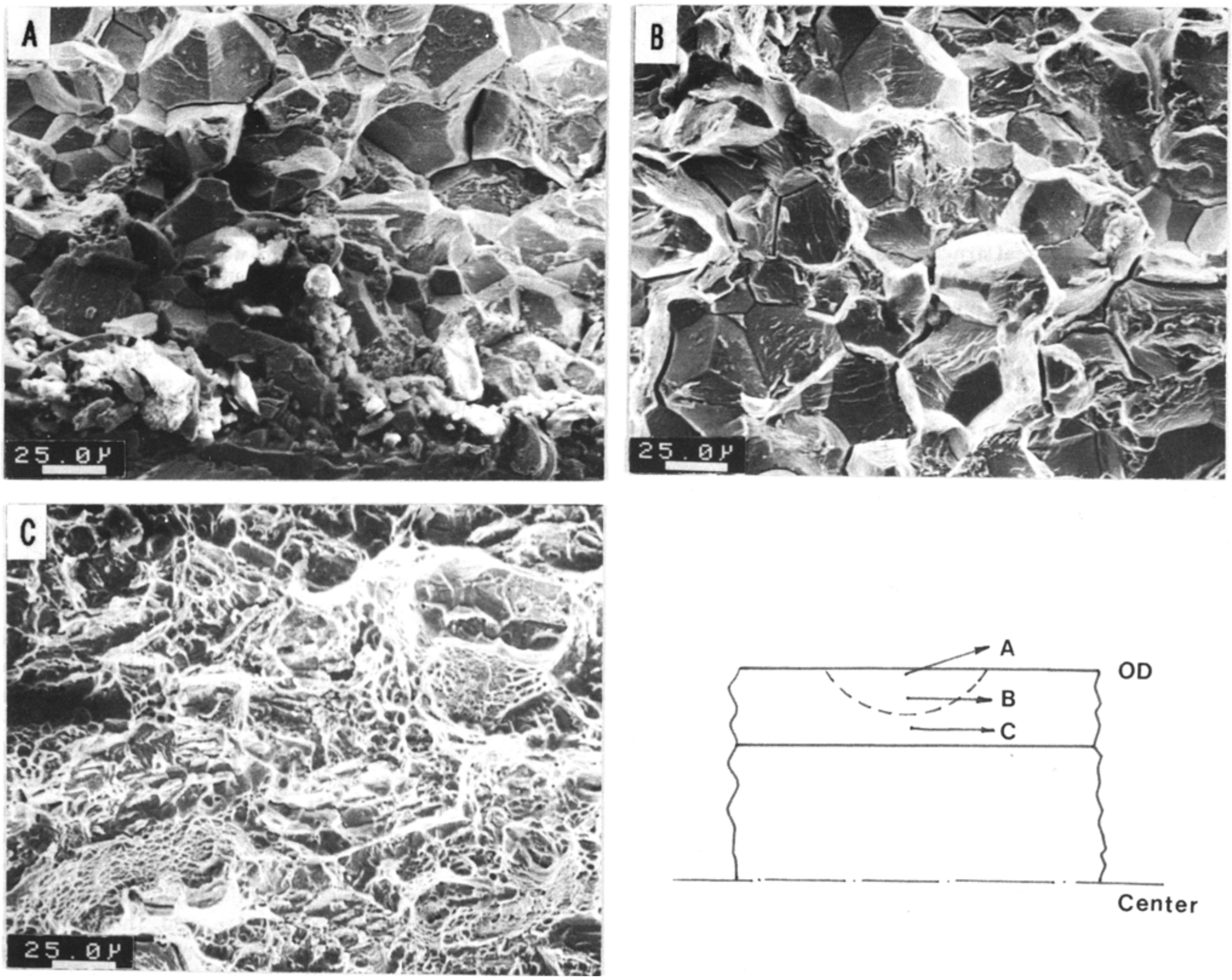

Fig. 2 SEM fracture surface exhibited a semi-elliptical crack region on vessel 1. The arrows indicate the locations of the observation.

cracks, and the fracture surface beyond this region was characterized by a primarily dimple type of ductile fracture. The SEM photographs of the fracture surface are shown in Fig. 2. The semi-elliptical intergranular crack region was associated with voids (see the black area in Fig. 2a), which are 25 to 50 µm from the outer diameter surface of the tube. Several such imperfections can be detected near the outer diameter surface within the intergranular crack region. In contrast to the vessel 1, the fracture surface of the vessel 2 which passed hydrotest presents a ductile fracture mode, as shown in Fig. 3. With the crack nucleation site clearly defined in the center of the vessel, a question arose as to whether this failure was some sort of anomaly, or could a non-through crack flaw with the observed dimensions consistently cause a brittle failure with this type of material under the service conditions? This question was all the more important considering the fact that the whole vessel was not undergoing NDT inspection, only the weldments. To answer this question, a stress and fracture toughness analysis was performed.

3. Stress Analysis

The pressure vessel was a tube with long axis in the Z-direction, loaded by an internal pressure, P_i. Using cylindrical coordinates, the stresses conditions can be expressed as follows:

$$\sigma_\theta = P_i \frac{a^2}{b^2 - a^2} + P_i \frac{1}{(b^2 - a^2)r^2} \quad [1]$$

$$\sigma_r = P_i \frac{a^2}{b^2 - a^2} - P_i \frac{1}{(b^2 - a^2)r^2} \quad [2]$$

$$\sigma_z = \frac{a^2 P_i}{b^2 - a^2} \quad [3]$$

where a is the inner radius, and b is the outer radius.

If P_i is equal to the proof pressure in the hydrotest, the maximum stress at the inner radius of the tube can be given as:

$$\sigma_\theta = 1027 \text{ MPa}$$

$$\sigma_r = -19 \text{ MPa}$$

$$\sigma_z = 503 \text{ MPa}$$

The stress distribution in the wall of the tube is shown in Fig. 4. If the pressure at which vessel 1 failed is taken into the calculation:

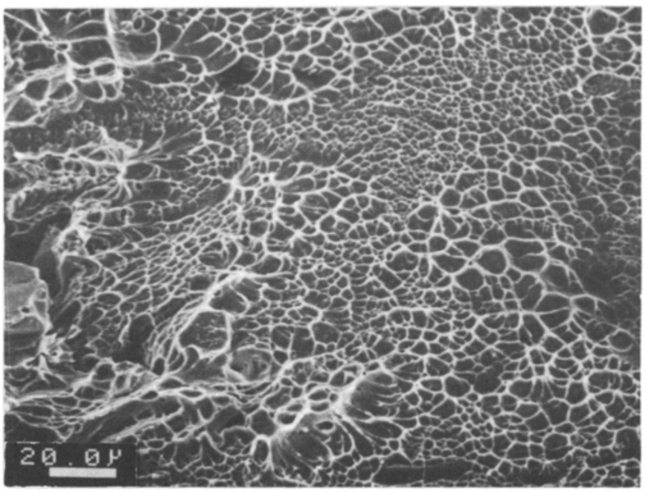

Fig. 3 SEM fracture surface of vessel 2 exhibiting a ductile fracture.

$$\sigma_\theta^{max} = 958 \text{ MPa}$$

The stress in Z direction, σ_z, is only one half of the stress in the hoop direction, σ_θ. σ_r is a small compressive stress that had no effect on the cracking of the vessels. The welds at either end are only subjected to one half of the stress applied on the wall of the tube in the hoop direction. This is consistent with the fracture examination that determined the crack was not from the welds. The stress in the hoop direction will reach a maximum value in the middle section of the vessels because less constraint is received from the end seals. Because the maximum stress is in the center section, any pre-existing flaw could be expected to nucleate a crack that would form along a relatively straight path in the longitudinal direction of the vessel. When the crack was propagated to certain length, shear deformation occurred, which created fracture paths 45° to the principal stress (hoop) direction. These shear crack paths are described in Fig. 1.

4. Fracture Mechanics Approach

Based on the observation of a surface semi-elliptical crack on the fracture surface of vessel 1, a fracture mechanics approach can be taken to estimate the stress-intensity factor, K_I, at fracture. If $K_I \approx K_{IC}$ of a material, failure during hydrotesting will be expected:

$$K_I = \frac{\sigma\sqrt{\pi a}}{\varphi} \cdot M1\ M2\ M_p \qquad [4]$$

Where σ is the applied maximum stress in the hydrotesting of vessel 1, and σ = 958 MPa, $M1$, $M2$, M_p are modification factors; for K_I, $M1 \times M2$ = 1.1.

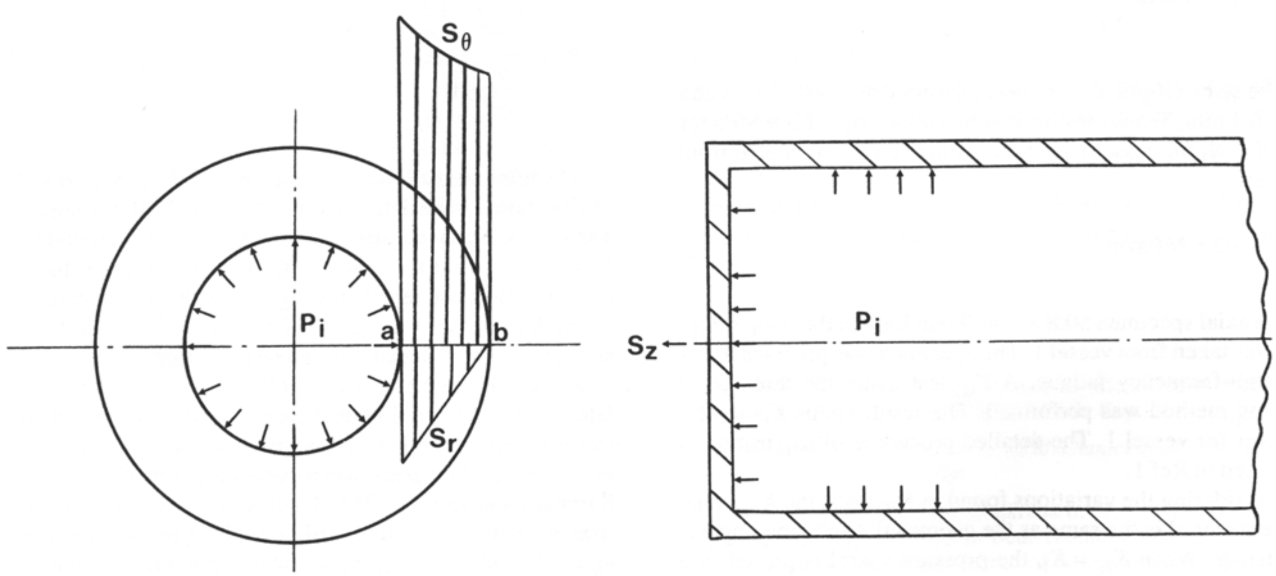

Fig. 4 Schematic of stress distributions on the pressure vessel.

$$M_p = \frac{\varphi}{\sqrt{Q}} \qquad [5]$$

where φ is an elliptical integral.

$$\varphi = \int_0^{\pi/2} (\sin^2 \varphi + \frac{a^2}{c^2} \cos \varphi)^{1/2} \, d\varphi \qquad [6]$$

The elliptical integral can be simplified by series expansion by taking the first two terms:

$$\varphi = \frac{\pi}{2}\left[1 - \frac{1}{4}\frac{c^2 - a^2}{c^2} - \frac{3}{64}\left(\frac{c^2 - a^2}{c^2}\right)^2 \cdots\right] = \frac{3\pi}{8} + \frac{\pi}{8}\frac{a^2}{c^2} \qquad [7]$$

Considering the plastic zone on the crack tip, one must use the effective crack length $a_f = a + r_y$ to replace crack length a. For plane-strain:

$$r_y = \frac{1}{4\sqrt{2\pi}}\left(\frac{K1}{\sigma_s}\right)^2 \qquad [8]$$

where σ_s is the yield strength. Equation 4 finally can be expressed as:

$$K_I = \frac{1.1\sigma\sqrt{\pi a}}{\sqrt{\varphi^2 - 0.212\left(\frac{\sigma}{\sigma_s}\right)^2}} = 1.1\sigma\sqrt{\frac{\pi a}{Q}} \qquad [9]$$

where

$$Q = \varphi^2 - 0.212\left(\frac{\sigma}{\sigma_s}\right)^2$$

The semi-elliptical crack was measured as a = 0.76 mm and $2C$ = 6.1 mm. Tensile testing results yielded σ_s = 1269 MPa for vessel 1. K_I for vessel 1 in hydrotesting can be calculated from Eq 9 as:

$$K_I = 43.8 \text{ MPa}\sqrt{\text{m}}$$

An axial specimen 50.8 × 196.9 mm long in the hoop direction was taken from vessel 1. The specimen was precracked using high-frequency fatigue. A K_{IC} test using the three-point bending method was performed. The result yields K_{IC} = 42.0 MPa$\sqrt{\text{m}}$ for vessel 1. The detailed procedure of K_{IC} testing is described in Ref 1.

Considering the variations found in K_{IC} tests, the K_{IC} value of the material is the same as the estimated K_I obtained by hydrotesting. When $K_{IC} = K_I$, the pressure vessel is placed in a critical condition in that a small variation in K_{IC} may cause a catastrophic failure during hydrotesting or during service. Because K_{IC} is related to other material properties, additional efforts have focused on evaluation of overall mechanical properties and microstructure of the two vessels.

Table 1 Mechanical testing results

Vessel No.	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Hardness, HRC	Bending strength, MPa
1	1358	1269	6	41.5	2351
2	1358	1207	6	40.5	2393

5. Mechanical Properties and Microstructure

Table 1 gives mechanical testing results of samples taken from vessels 1 and 2. Tensile test data were based on an average of ten samples. The tensile results show that the material of vessel 1 exhibits an average 5% higher yield strength than that of vessel 2, which usually indicates a possible lower K_{IC} value. Therefore, to avoid brittle fracture during hydrotesting, the K_{IC} value of the material should be increased through proper heat treatment. On the other hand, plastic deformation is not permitted in high-pressure vessels. A compromise must be made between K_{IC} and the yield strength of the material. The minimum yield strength under the hydrotest pressure without yielding of the material can be obtained by Von Mises yielding criteria.

Von Mises suggested that yielding occurs when J_2 reaches a critical value:[2]

$$J_2 = k^2 \qquad [10]$$

in which J_2 is the second deviatoric stress invariant; k is a material parameter; $\sigma_s = \sqrt{3}k$ at uniaxial tensile stress. Substituting σ_θ and σ_s into Eq 9 yields

$$P_i = \frac{\sigma_s\left(\frac{b^2}{a^2} - 1\right)}{\frac{b^2}{a^2} + 1} \qquad [11]$$

The minimum allowable yield stress at the proof pressure of 19,500 MPa can be determined as σ_s = 1027 MPa. Considering a safety factor, a yield stress of 1150 to 1200 MPa should be sufficient to prevent the material from yielding under the proof pressure. Because tensile testing shows that the average yield strength of vessel 1 is 1269 MPa, it is obvious that the yield strength can be reduced through heat treating.

K_{IC} can be significantly affected by microstructure and related heat treatment. Figure 5 shows the microstructure of two samples. Because the Beta-C alloy contains a sufficient amount of beta phase stabilizers, when quenching from above the β/α + β transus temperature (755 °C), it results in a bcc lattice β matrix. Strength is then achieved by α phase precipitation during aging. In both samples, α precipitates exhibited a Widmanstätten structure, which consists of groups of α phase needles lying with their long axes parallel to crystalline planes of β matrix.

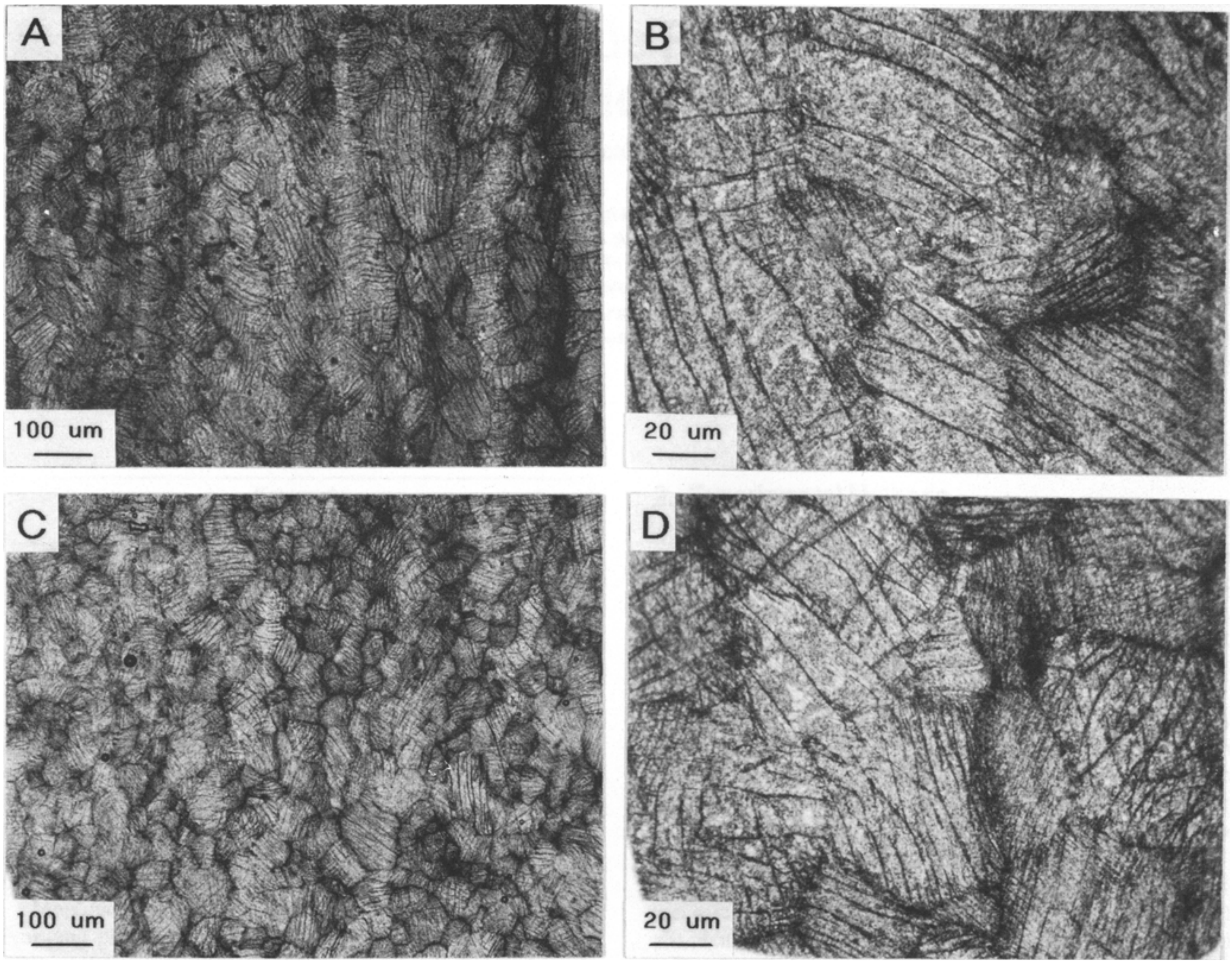

Fig. 5 Microstructure of the Beta-C titanium alloy. (a) and (b) From vessel 1. (c) and (d) From vessel 2.

Other types of α precipitates are very finely dispersed particles, which cannot be clearly distinguished by optical microscopy. These fine precipitates appear to be type 2 α precipitates. It was found that the β matrix of vessel 1 in some regions exhibited a duplex grain structure, whereas vessel 2 exhibited a uniform β grain structure. The duplex grain structure may reflect localized nonuniform deformation, which may have occurred during thermomechanical processing during fabrication of the vessel.[3]

6. Conclusions

The brittle fracture of the high-pressure vessel that occurred during hydrotesting was caused by a surface defect. A complete intergranular fracture was observed in the area of the crack origin while the surrounding area exhibited microvoid coalescence. The presence of intergranular cracking in a localized area significantly reduced fracture toughness and led to a catastrophic fracture.

Examination of the fracture toughness of the material and stress analysis of the vessel revealed that K_{IC} of the material is very close to the value of the stress intensity factor K_I during hydrotesting, which places the structure in a critical condition to fracture.

To avoid brittle fracture under the observed service conditions, heat treatment must be modified so as to increase toughness while maintaining a minimum yield strength of 1150 to 1200 MPa.

References

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